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Anisotropy of Particle Cracking Damage Development in an Al-Mg-Si Base Wrought Aluminum Alloy Under Uniaxial Compression

by

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ABSTRACT

Particle cracking is an important damage mode in numerous engineering alloys having anisotropic microstructures. In this contribution, cracking of anisotropic Fe-rich intermetallic particles in an extruded Al-Mg-Si base alloy has been quantitatively characterized as a function of compressive strain for two loading directions. In the microstructural space of this alloy, the Fe-rich second phase particles rotate when a compressive load is applied parallel to the extrusion direction. The particle rotations in turn affect the particle cracking process. Due to microstructural anisotropy, at low compressive strains, the number fraction of cracked Fe-rich particles is higher in the specimens where the loading direction is perpendicular to the extrusion axis as compared to that in the specimens where the loading direction is parallel to the extrusion axis. However, due to particle rotations, the reverse is true at the high strain levels. At high compression strain levels, the rate of increase in the number fraction of cracked particles with strain decreases monotonically with the increase in the strain, and consequently, the number fraction of cracked particles approaches a saturation level when the loading direction is perpendicular to the extrusion direction. On the other hand, the rate of increase in the number fraction of particles with strain does not decrease with the increase in the strain, when the loading direction is parallel to the extrusion direction. These differences in the damage evolution are explained on the basis of particle rotations.

I. INTRODUCTION

6XXX series of wrought Aluminum alloys are widely used for structural applications. Ductile fracture of these alloys (and numerous other materials) involves cracking of brittle phase inclusions/particles in the microstructure, the growth of the micro-voids at the particle cracks, and micro-void coalescence. Therefore, to understand the damage evolution and fracture processes in such materials, it is of interest to quantitatively characterize damage initiation by particle cracking. Such quantitative data provides critical input for the development of predictive damage evolution models [1,2].

There have been numerous experimental and theoretical studies on particle cracking [3-10]. However, most of the earlier investigations concern particle cracking only under applied <u>tensile</u> stress. Damage evolution due to particle cracking under other loading conditions and stress states has received little attention. To the best of authors' knowledge, cast A356 Al-alloy is the only material in which damage evolution has been quantitatively characterized as a function of loading [11,12], temperature [13] and strain rate [14]. Further, most of the past experimental investigations on particle cracking in the monolithic alloys have been performed on <u>isotropic</u> microstructures, where the damage development does not depend on the direction of the applied load. However, numerous structural alloys containing brittle phase particles/inclusions have anisotropic microstructures. For example, microstructure of an extruded 6061 Al-alloy contains Fe-rich intermetallic particles that are mostly aligned parallel to the extrusion direction (see Figure 1). In such microstructures, the damage evolution initiated by particle cracking depends on the direction of the applied load with respect to the axis of microstructural anisotropy.

Particle cracking (i.e., damage/void nucleation) as well as micro-void growth around the cracked particles can occur under an externally applied tensile load. On the other hand, under uniaxial <u>compression</u>, only the particle cracking (damage nucleation) is observed, and there is no micro-void growth around the cracked particles. Therefore, in order to focus on the damage nucleation process, it is of interest to quantitatively characterize particle cracking under uniaxial compressive loads.

The objective of this contribution is to report quantitative experimental observations on the cracking of anisotropic Fe-rich intermetallic particles in an extruded 6061 Al-alloy under uniaxial compression, when the load is applied parallel and perpendicular to the extrusion axis (which is the axis of microstructural anisotropy). It is shown that the damage due to particle cracking significantly depends on the loading direction. At low compressive strains, the number fraction of cracked Fe-rich particles is higher in the specimens where the loading direction is perpendicular to the extrusion axis as compared to that in the specimens where the loading direction is parallel to the extrusion axis. However, the reverse is true at the high strain levels. At high compression strain levels, the number of fraction of cracked particles appears to reach a saturation level when the loading direction is perpendicular to the extrusion direction, whereas no such saturation level is observed when the loading direction is parallel to the extrusion direction. It is also observed that the Fe-rich particles rotate when the compressive load is applied parallel to the extrusion direction. The particle rotations in turn affect the particle cracking process. The differences in the damage evolution due to different loading directions are explained on the basis of particle rotations.

II. EXPERIMENTAL

A. Materials

The experiments were performed on the specimens drawn from an extruded round bar (88 mm diameter) of 6061 Al-alloy (T651 condition) supplied by ALCOA. The chemical composition of the alloy is given in Table-I.

B. Mechanical Tests

In the extruded Al-alloy bar stock, microstructural /chemical gradients may exist in the radial direction. To ensure that all test specimens have statistically similar microstructure and the same alloy chemistry, the specimens were extracted from the bar stock at a radial distance of 20 mm from the bar center.

MTS81- Axial-Torsional servo-hydraulic test frame was used for the compression tests. In one set of specimens, the quasi-static uniaxial compression tests were performed with loading direction parallel to the extrusion axis, whereas in the second set of specimens, the compression tests were conducted by applying the load perpendicular to the extrusion axis. Both set of experiments were performed on cylindrical specimens of 9 mm diameter and 12.5 mm length at the strain rate of 2 x 10^{-4}/sec. Concentric grooves were machined into the ends of the specimens in which a Mo based lubricant was placed. The lubrication was necessary to ensure homogeneous deformation of the specimens. The specimens were examined at the end of each test; no barreling effects were seen. Thus, homogeneous deformation conditions can be assumed for the compression tests. These quasi-static tests were interrupted at different strain levels ranging from 3.75% to 80% to study the particle cracking phenomena as a function of strain and loading direction. Figure 2 and 3 show stress-strain curves for compression loading applied in the two directions of interest.

C. Metallography

The specimens were cut in the center along vertical planes containing the applied loading direction and the extrusion axis of extruded bar, and then they were mounted and polished by using standard metallographic techniques. The microstructures were observed under anoptical microscope in the unetched condition. Figure 1 shows a typical microstructure of an unstrained specimen in an unetched condition. Observe that the microstructure contains two types of particles in the aluminum-rich matrix. Light gray particles are the Fe-based intermetallics, and the dark particles are the Mg_2Si intermetallics. Both type of particles are mostly oriented parallel to the extrusion axis. Thus, the extrusion axis is the axis of microstructural anisotropy. Figure 4 depicts the microstructure of deformed specimens showing cracked Fe-rich intermetallic particles. In 6061 Al-alloy, the damage due to cracking of Mg_2Si intermetallics is observed to be negligible in comparison to that due to cracking of Fe-based intermetallics. Therefore, in the present study, cracking of only the Fe rich intermetallics has been quantitatively characterized.

D. Quantitative Metallography

To quantify the cracking of Fe-rich intermetallic particles, the plane containing the loading direction and extrusion axis was chosen as the metallographic plane of observation. The two-dimensional number density and geometric attributes of cracked intermetallic particles such as the major axis, minor axis, perimeter, area and the equivalent diameter were measured by using interactive image analysis. In order to quantify the anisotropy of Fe-rich intermetallics particles, the angles between the extrusion direction and major axes of large number of particles (about 5000 particles in each specimen) were measured by using image analysis, and morphological orientation distributions of the particles were computed from these data sets. To minimize the edge effects, all measurements were performed on montages of large number of contiguous fields of view (350 to 400 fields) grabbed using the technique developed by Louis and

Gokhale [15]. The geometric attributes of broken/cracked particles were measured by using the same montages via interactive image analysis.

III. RESULTS AND DISCUSSION

The number fraction of cracked Fe-rich intermetallic particles f is equal to the number of cracked Fe-rich particles per unit area of metallographic plane divided by the overall number of Fe-rich particles per unit area in the bulk microstructure. Figure 5 shows the plot of f versus compressive strain for compression loading parallel to the extrusion axis as well as for the set of specimens having compression loading perpendicular to the extrusion axis. These data show that there are significant differences in the evolution of particle cracking damage for the two loading directions, i.e., the damage evolution is anisotropic in nature. At low compressive strains the number fraction of cracked particles f is larger for the loading direction perpendicular to the extrusion axis. However, the reverse is true at the high strain levels. Further, the rate of increase of the number fraction of particles f with compressive strain ε, i.e., $[df/d\varepsilon]$, *decreases* with the increase in the strain when the compressive load is applied perpendicular to the extrusion axis, whereas it does not appear to decrease when the compressive load is applied parallel to the extrusion axis. Therefore, the number fraction of the cracked particles may approach a saturation level at high compressive strains when the loading direction is perpendicular to the extrusion axis, whereas no such saturation level may exist when the loading direction is parallel to the extrusion axis.

The compression stress-strain curves for the two loading directions of interest (i.e., direction parallel to the extrusion axis and the direction perpendicular to the extrusion axis) are shown in Figures 2 and 3. Interestingly, there are no significant differences in these stress-strain curves. Therefore, the global stress-strain relationship is not sensitive to the dependence of the particle cracking damage evolution on the loading direction. Consequently, the observed differences in the particle cracking damage development cannot be explained on the basis of conventional continuum plasticity theories.

Figure 6 compares the orientation distribution of the bulk Fe-rich particles (note that this distribution includes both undamaged and cracked particles) in the unstrained specimen with the corresponding distribution in the 70% compression strain specimen, where the compressive load is applied parallel to the extrusion axis. In the unstrained specimen, 77% of the particles have their orientation angles between 0 to 30 degrees, and only 7% have their orientation angle between 60 and 90 degrees. On the other hand, in the specimen strained to 70% compression strain, about 43 % of the particles have their orientations in the range of 0 to 30 degrees, and 30 % of the particles are oriented at angles in the range of 60 to 90 degrees with respect to the extrusion axis/loading direction. In other words, the percentage of the particles in the orientation range 60 to 90 degrees in the bulk population (damaged and undamaged) has increased from 7% to 30% when the specimen is strained to 70% strain level when the compressive load is applied parallel to the extrusion axis. Further, the average orientation angle of the bulk (damaged and undamaged) Fe-rich particles has increased from 24 degrees in the unstrained specimen to 36 degrees in the specimen with 70% compressive strain. Note that these orientation data have been obtained by measuring orientations of about 5000 particles in each specimen, and therefore, the data are robust. *These data clearly demonstrate that the brittle Fe-rich intermetallic particles rotate during the plastic deformation of the specimens when the compressive loading direction is parallel to the extrusion axis, and they tend to align themselves along the direction perpendicular to the loading direction (extrusion axis), which is a principal stretch direction.* All current particle cracking theories do not explicitly account for the re-orientation of brittle particles during plastic deformation. Therefore, these damage evolution theories do not capture the entire evolution of the microstructure morphology which can not be decoupled from the damage process. Particle rotations can bring the particles in the orientation ranges that facilitates particle cracking. Figure 7 shows a plot of the average orientation angle of the overall bulk Fe-rich particles (damaged and undamaged) versus compression strain when the load is applied parallel to the extrusion axis. The average orientation angle increases with the compressive strain, implying that the particle rotations bring more and more particles in the orientations perpendicular to the extrusion axis, which is the direction of <u>induced</u> tensile stress, when a compressive load is applied parallel to the extrusion direction.

Figure 8 compares the orientation distribution of the bulk Fe-rich particles (note that this distribution includes both undamaged and cracked particles) in the unstrained specimen with the corresponding distribution in the 80% compression strain specimen, where the compressive load is applied <u>perpendicular</u> to the extrusion axis. There are no significant differences in the two morphological orientation distribution functions. The average orientation angle is also about the same (22.6 degrees) in both the specimens. Therefore, significant particle rotations do not take place when a compressive load is applied perpendicular to extrusion axis (which is the axis of microstructural anisotropy). In this case, particles remain relatively stationary with the grain structure which simply flattens out in shape.

The progression of particle damage in this material is intimately connected with the particle rotations and microstructural anisotropy. In Figure 4a, where compressive load is applied parallel to the extrusion axis, most of the cracks are parallel to the loading direction /extrusion axis, and therefore, i.e., they are perpendicular to the direction of induced tensile stress. On the other hand, in Figure 4b, where the compressive load is applied perpendicular to the extrusion axis, most of the cracks are perpendicular to the extrusion axis, i.e., they are perpendicular to the induced tensile stress direction. These observations as well as those of the other investigators [1, 6-9, 11-13] strongly support the hypothesis that the particle cracking is governed by maximum principal tensile stress component (either applied or induced). Further, it is also well known that the particles that are oriented parallel to the direction of applied/induced tensile stress have a much higher probability of cracking [3,6,11,16]. When a uniaxial compressive load is applied parallel to the extrusion axis, the induced maximum principal tensile stress component is perpendicular to the extrusion axis. However, in the present anisotropic microstructure, only 7% of the particles have orientations in the range of 60 to 90 degrees, i.e., almost perpendicular to extrusion axis and parallel to the induced tensile stress. In other words, when compressive load is applied parallel to the extrusion axis (at least initially) very few particles have orientations that facilitate particle cracking. On the other hand, when the compressive load is applied perpendicular to the extrusion axis, the induced tensile stress component is parallel to the extrusion axis, and about 77% of the particles have their orientations close to parallel (0 to 30 degrees range) to the induced tensile stress direction, and therefore conducive to particle cracking. Consequently, at low compressive strain levels, the fraction of cracked particles is expected to be larger for the specimens where the loading direction is perpendicular to the extrusion axis as compared to that in the specimen where the loading direction is parallel to the extrusion axis, which is exactly what is observed experimentally (see Figure 5). However, particle rotations become important at the higher strain levels. Significant particle rotations occur at high strains, when compressive load is applied parallel to the extrusion axis. As the applied compressive load / strain increases, the particle rotations bring more and more new particles in the orientation range of 60 to 90 degrees, i.e., almost parallel to the induced tensile stress (see Figures 6 and 7), which facilitates cracking of additional particles. Therefore, the number fraction of cracked particles steadily increases with the compressive strain when the applied load is parallel to the extrusion axis (see Figure 5). On the other hand, no significant particle rotations occur when a compressive load is applied perpendicular to the extrusion axis (see Figure 8), as most of the particles are already oriented almost parallel to the induced tensile stress direction (extrusion direction). The large particles that have high probability of cracking, crack at lower strain (stress) levels, induced tensile stress is not sufficiently high to crack very small particles, and due to lack of significant particle rotations, no new particle are brought in the orientations that facilitate further particle cracking. Consequently, the rate of change of number fraction of cracked particles with the compressive strain decreases with the increase in the strain. Thus, the combination particle rotations and microstructural anisotropy lead loading direction dependence of the particle cracking damage accumulation.

Theoretical analysis of brittle particle rotations in solid polycrystalline matrices has not been reported in the literature. However, particle rotations in viscous fluid matrices have been modeled [17-20]. The rotation of particles in deforming crystalline materials can be approached from several different points of view. If the particles are small with respect to the grain size (such as those in the present alloy), then particle rotations are expected to be strongly coupled with the rotations of the matrix grains. For the FCC Al-rich matrix of the 6061 alloy, an idealized planar double slip model can be used to qualitatively describe the crystal (grain) rotations arising from finite strain inelastic deformation. The local rotations of the grains and local compatibility of deformation governs the rotation of particles. Thus, issues such as grain size, local textures, particle size, spacing, aspect ratio, and initial orientations are expected to be important parameters in determining the rotations of particles. High aspect ratio particles with large inter-particle spacing may potentially undergo more rotations than equiaxed particles that are tightly spaced in the same ductile matrix. Therefore, the present data demonstrate that the rotations of particles and the factors that influence them are very important for modeling the differences in damage evolution in anisotropic microstructures.

IV. SUMMARY AND CONCLUSIONS

Cracking of anisotropic Fe-rich intermetallic particles in an extruded 6061 Al-alloy has been quantitatively characterized as a function of compressive strain for two loading directions. The Fe-rich particles rotate when the compressive load is applied parallel to the extrusion direction. The particle rotations in turn affect the particle cracking process. Due to microstructural anisotropy, at low compressive strains, the number fraction of cracked Fe-rich particles is higher in the specimens where the loading direction is perpendicular to the extrusion axis as compared to that in the specimens where the loading direction is parallel to the extrusion axis. However, due to particle rotations, the reverse is true at the high strain levels. At high compression strain levels, the number fraction of cracked particles appears to reach a saturation level when the loading direction is perpendicular to the extrusion direction, whereas no such saturation level is observed when the loading direction is parallel to the extrusion direction.

V. ACKNOWLEDGEMENT

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VII. LIST OF FIGURE CAPTIONS

Figure 1: Microstructure of unstrained 6061 Al-alloy.

Figure 2: Stress-strain curve of 6061 Al-alloy under uniaxial compression when loading direction was parallel to extrusion axis.

Figure 3: Stress-strain curve of 6061 Al -alloy under uniaxial compression when loading direction was perpendicular to extrusion axis.

Figure 4: Microstructure of a strained specimen showing cracked Fe-rich intermetallic particles.

Figure 5: Variation of 2D number fraction of Fe-rich damaged intermetallic particles with respect to compressive strain for loading direction parallel and as well as perpendicular to the extrusion axis.

Figure 6: Comparison of morphological orientation distribution of Fe-rich bulk intermetallic particles in unstrained specimen and the specimen deformed to 70% compressive strain when loading direction was parallel to extrusion axis.

Figure 7: Variation of average orientation angle of the overall bulk Fe-rich particles with compressive strains for loading direction parallel to extrusion axis.

Figure 8: Comparison of morphological orientation distribution of Fe-rich bulk intermetallic particles in unstrained specimen and the specimen deformed to 80% compressive strain when loading direction was perpendicular to the extrusion axis.

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Table-I: Chemical Composition of 6061 Al-alloy

TABLE-I

Chemical Composition of 6061 Al-alloy

Element	Zn	Ti	Si	Mn	Mg	Fe	Cu	Cr	Al
Wt pct	0.02	0.01	0.65	0.04	1.06	0.37	0.28	0.2	Balance

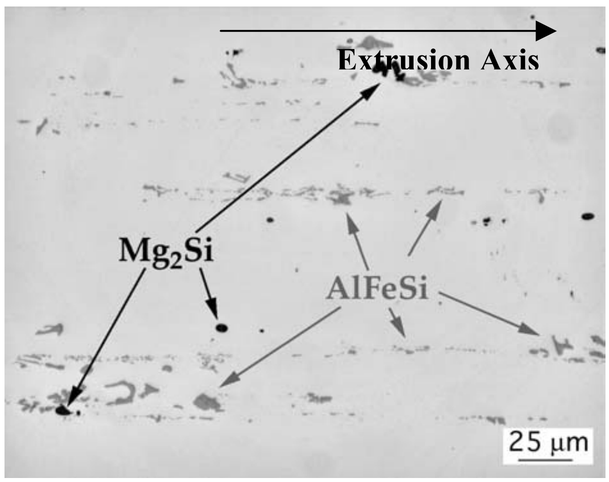


Figure 1: Microstructure of unstrained 6061 Al-alloy.

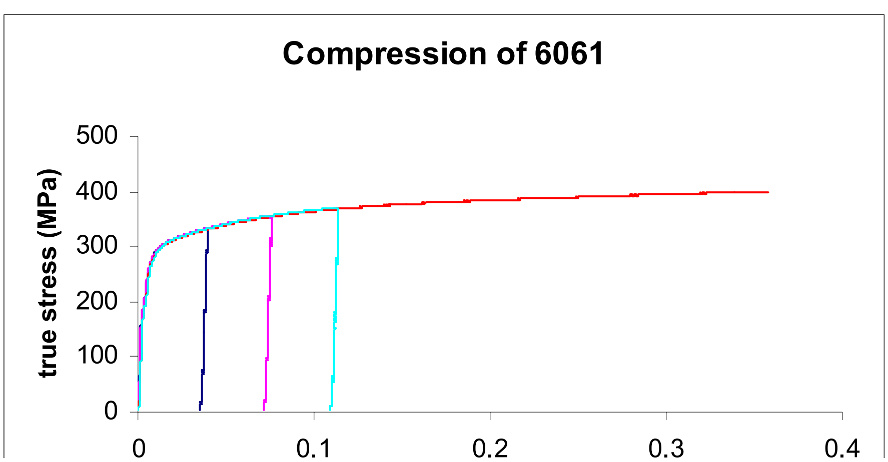


Figure 2: Stress-strain curve of 6061 Al-alloy under uniaxial compression when loading direction was parallel to extrusion axis.

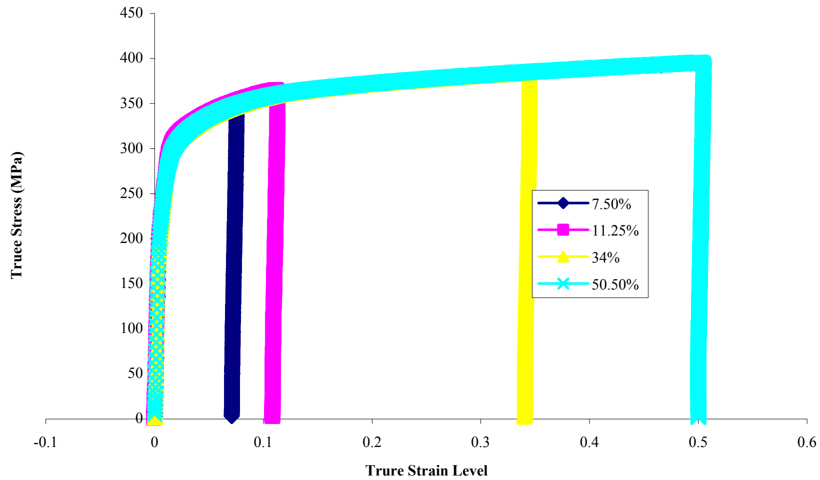
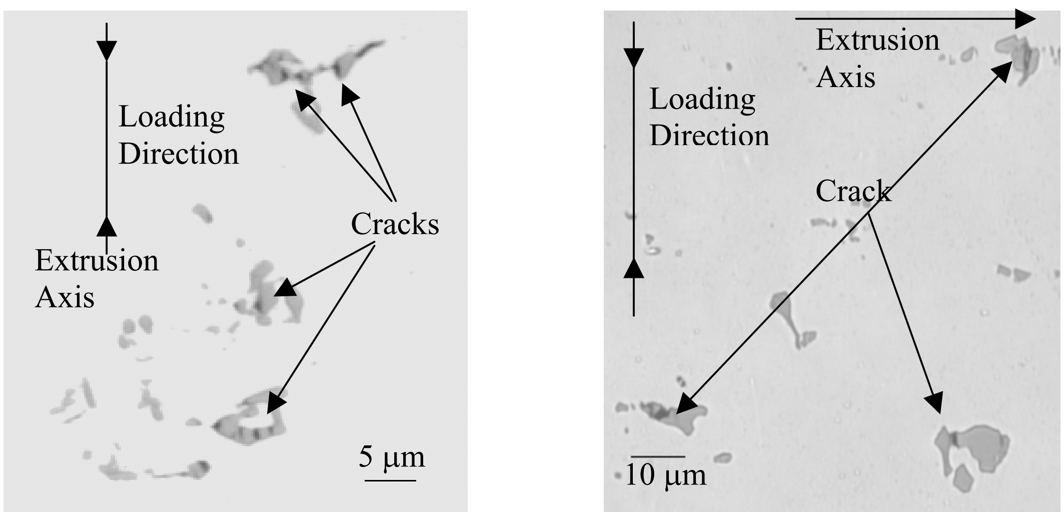


Figure 3 Stress-strain curve of 6061 Al-alloy under uniaxial compression when loading direction was perpendicular to extrusion axis.



70% On-Axis Compression

Figure 4 Microstructure of a strained specimen showing cracked Fe-rich intermetallic particles.

80% Off-Axis Compression

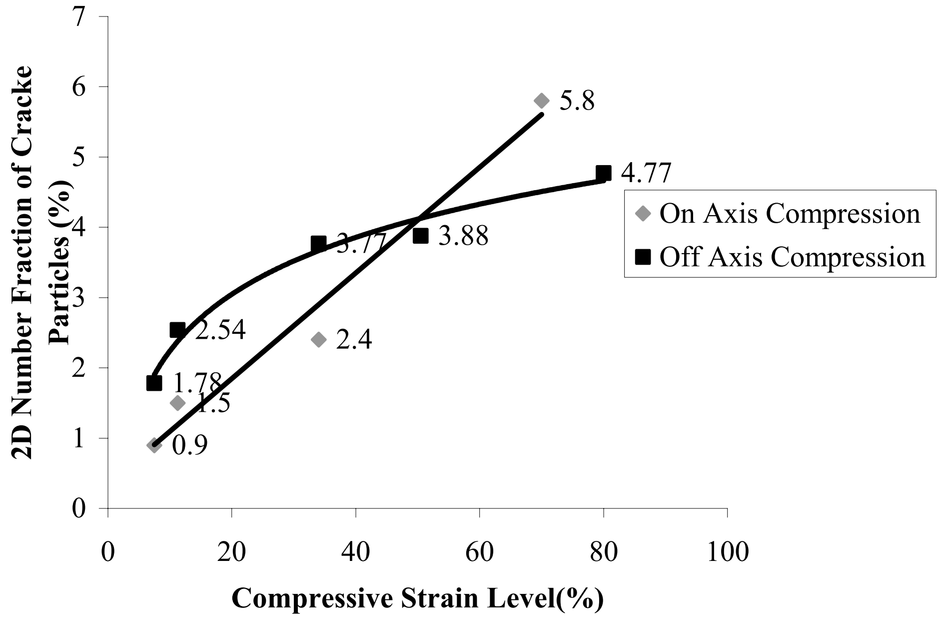


Figure 5 Variation of 2D number fraction of Fe-rich damaged intermetallic particles with respect to compressive strain for loading direction parallel and as well as perpendicular to the extrusion axis.

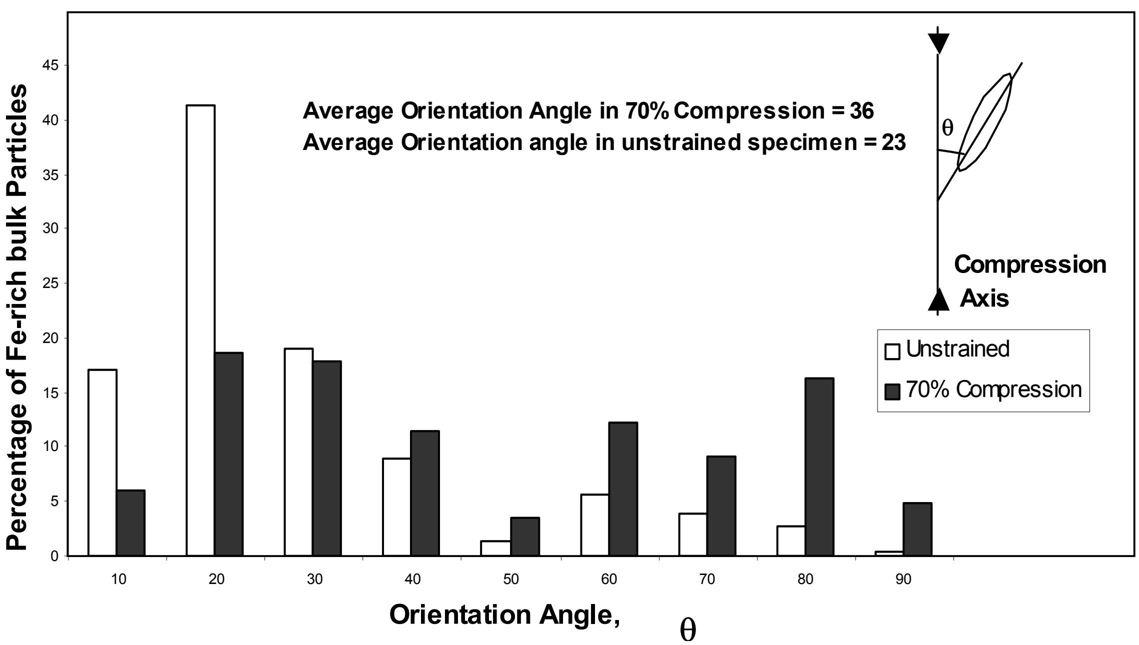


Figure 6: Comparison of morphological orientation distribution of Fe-rich bulk intermetallic particles in unstrained specimen and the specimen deformed to 70% compressive strain when loading direction was parallel to extrusion axis.

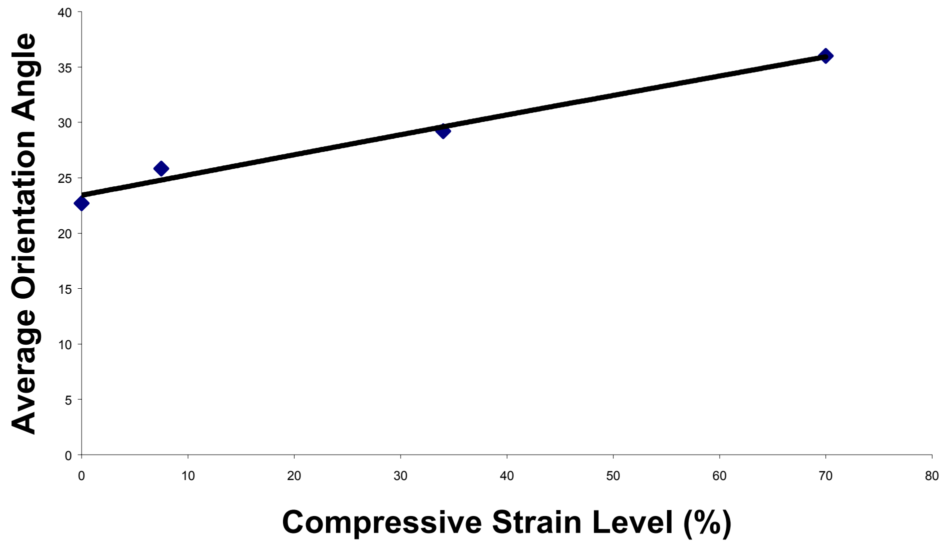


Figure 7: Variation of average orientation angle of the overall bulk Fe-rich particles with compressive strains for loading direction parallel to extrusion axis.

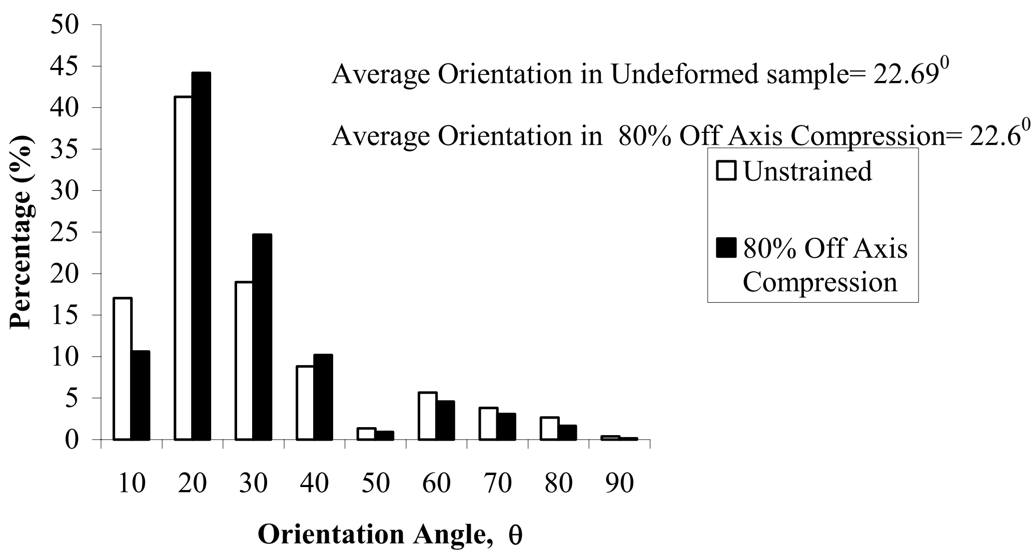


Figure 8 Comparison of morphological orientation distribution of Fe-rich bulk intermetallic particles in unstrained specimen and the specimen deformed to 80% compressive strain when loading direction was perpendicular to the extrusion axis.